

REUSABLE PROPULSION ARCHITECTURE FOR SUSTAINABLE LOW-COST ACCESS TO SPACE¹

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ABSTRACT

The primary obstacle to any space-based mission is, and has always been, the cost of access to space. Even with impressive efforts toward reusability, no system has come close to lowering the cost a significant amount. It is postulated here, that architectural innovation is necessary to make reusability feasible, not incremental subsystem changes. This paper shows two architectural approaches of reusability that merit further study investments. Both 'inherently' have performance increases and cost advantages to make affordable access to space a near-term reality. A rocket launched from a subsonic aircraft (specifically the Crossbow methodology) and a momentum exchange tether, reboosted by electrodynamics, offer possibilities of substantial reductions in the total transportation architecture mass - making access-to-space cost-effective. They also offer intangible benefits that reduce risk or offer large growth potential. The cost analysis indicates that approximately a 50% savings is obtained using today's aerospace materials and practices.

NOMENCLATURE

C_h \equiv cost of expended launch vehicle hardware
 C_o \equiv cost of launch site operations
 C_p \equiv cost of propellant
 C_T \equiv total launch cost
 f \equiv mass fraction of hardware expended
 L \equiv processing hours per unit dry mass
 M_{PL} \equiv payload mass
 M_S \equiv dry mass
 P \equiv ratio of propellant mass to payload mass M_P / M_{PL}
 R \equiv ratio of dry mass to payload mass M_S / M_{PL}

BACKGROUND

The access-to-space has been more a challenge of affordability than of technical hurdles. Often "reusability" has been the answer. Nevertheless: reusable Earth-To-Orbit (ETO) programs have been unable to achieve their goals despite tremendous time and resources allocations. Furthermore, reusable space-based systems, such as depots or electric propulsion tugs, are more difficult to develop as reusable systems and have only marginal overall effect on ETO costs because they can not operate efficiently deep in the gravity well. Countless studies have been performed on approaches to reduce the expense of space access. At the 2005 AIAA Joint propulsion Conference, scores of new papers were published on "ideal" ETO options, but many fail to include sensible performance and reusability constraints. In fact, to appear "realistic", most feature existing hardware that has been proven to be cost-ineffective!^{1,2,3,4} Yet, ETO cost continues to be the impediment to privatization of space and the primary challenge in any truly 'sustainable' human exploration architecture.

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In 1994, Michael Griffin and William Claybaugh published a cost model for space transportation.⁵ Their methodology scrutinized the characteristics that any cost-effective, space transportation system must have, rather than evaluate specific transportation concepts. It summarized the cost of a space launch as the cost of expended launch vehicle hardware, launch vehicle propellant, and launch site operations.

$$C_T = C_h + C_p + C_o \quad (1)$$

The cost model further defined the expended launch vehicle hardware cost as a specific cost of launch vehicle hardware multiplied by the mass fraction of expended hardware and the launch vehicle dry mass.

$$C_h = c_h f M_s \quad (2)$$

Propellant costs were very straightforward:

$$C_p = c_p M_p \quad (3)$$

Also, operations cost were set equal to an hourly rate multiplied by the required hours or processes necessary to prepare the launch vehicle for flight. This includes refurbishments between flight, as well as launch site preparation.

$$C_o = c_L L M_s \quad (4)$$

For practical purpose, it is more relevant to place everything in terms of payload mass; therefore, they define a dry-mass to payload-mass fraction, R , and a propellant-mass to payload-mass fraction, P , which leads us to:

$$C_T = ((c_h f R) + (c_p P) + (c_L L R)) M_{PL} \quad (5)$$

Or a specific total launch cost of:

$$C_T = c_h f R + c_p P + c_L L R \quad (6)$$

Equation six gives a relationship that can be used to compare specific payload launch costs in terms of weighting factors that must be optimized. It is the starting point for the proposed architecture cost analysis. Fundamentally, we want to minimize the amount of hardware expended for each launch, the fraction of dry-mass to payload-mass, the amount of propellant required, and the amount of labor hours into manufacturing the required hardware. Also, any reduction in cost of propellant, hardware, or labor is desirable. These are all intuitive statements.

ASSUMPTIONS

The specific architecture analysis proceeds along conservative assumptions. The cost of labor for building, testing, etc., of hardware is not likely to see any major reduction from current costs associated with processing space qualified hardware. The cost of labor in industry is fairly constant in terms of labor mix (e.g., ratio of engineers to lower skilled support laborers or senior administrators to administrative staff). Outsourcing work to other countries is one method industries have used to reduce labor costs; however, this is assumed not reasonable for our national space program. Automation of processes is another method of reducing labor costs, but for flight rates even as high as one per week, this is still impractical. For the initial estimate, the cost of labor is assumed at an average of \$150,000 per man-year.

The cost of propellant for manned spaceflight nominally represents 5% of the launch cost. There is currently no foreseeable reduction in propellant costs. Moreover, with higher energy prices, production of propellants costs should increase. This would slightly favor higher specific impulse approaches or other propellant eliminating approaches such as proposed here. It is worth noting that if sustainable architectures make use of in-situ propellants, direct propellant cost (i.e., production cost) will rise several orders-of-magnitude and an even greater emphasis

would be placed on reducing the required propellant. For this study, the cost of propellant is assumed to remain constant at \$2/kg.

The last major expenditure is the cost of hardware. Hardware costs are a function of complexity and production quantity. Table 1 lists the expected average cost per unit hardware for common transportation devices.⁶ Average cost is also reduced by the length of time the device has been in existence and the resources applied toward optimization, both of which correspond with the quantity produced per year in these three vehicle categories.

Table 1: Cost of Transportation Devices

	C_h	Quantity Produced
Rockets	\$2500 / kg	10 – 100
Airplanes	\$1000 / kg	100 – 1000
Cars	\$3 - \$5 / kg	10,000 – 100,000

The complexity of aircraft and rockets in terms of hardware, avionics, and manufacturing quality control are both on the same order, however, the quantity of aircraft produced can allow for assembly line production and often results in substantial cost savings. Subsonic aircraft also operate far below engineering limits, where as ETO vehicles operate on the very edge of performance, much the way Formula 1 racecars or drag strip racers do when compared with the common automobile. That slim engineering margin significantly increases cost in both cases, because of the care that must be taken to ensure to never exceed catastrophic limits. With the aim of reducing the high risk of failure to acceptable levels, quality control, material selection, engineering designs and a thorough understanding of every physical detail are all pursued to a premium level. And such perfection ramps the expense exponentially higher; more than doubling the price between a Ferrari and a true Formula 1 race car!⁷

CHANGE IN PARADIGM

There is no concrete evidence that any significant reductions to the cost of access to space have ever been achieved. This is due to: the difficulty of discerning accurate budgetary data for any individual space launch; the never ending pursuit of technical performance (i.e., bigger payloads, greater efficiency, higher reliability, etc.); the exponential nature of costs to achieve slimmer engineering margins; the difficulty of drawing the line as to when any one program starts or stops. An honest assessment of ETO costs shows no major improvement will be made anytime soon. That is because the costing methodology assumes the same launch architecture that has been used since payloads were first launched into space. Every rocket market analysis has relied on huge increases in launch rate (expendable or reusable) to even imagine closing the gap.⁸ The physics of sending payloads into space will never change, but the way payloads are sent into space can and most likely should.

The first, and most obvious, method of reducing the cost to space is to replace the largest and most expensive ETO component, the booster stage, with the most efficient and mature commercial hardware that can do about same job. The concept of an air-launched rocket is far from new or novel. However, the specific air launch trade space presented here has not been embraced in sufficient depth. The principal air launch characteristics consist of: horizontal takeoff, a reusable aircraft, a conventional rocket, a separation event and aircraft fly-back.

A horizontal takeoff can significantly reduce the launch site operations cost by eliminating the specialized launch pad, tower, etc. and their associated expense of vertical integration. Because a horizontal takeoff only requires a runway, an air launch approach can use an existing runway and share launch site operations cost with conventional aircraft. Horizontal air launch is still distinct from conventional aircraft operations and will require specialized personnel to properly mount the staged rocket and payload, but the time and quantity of personnel required is greatly reduced, as well as, that of ground support equipment. With thousands of people currently working to sustain vertical launch capabilities and assembly, it is reasonable to assume that number can be reduced to hundreds; or a factor of ten for the parameter 'L'. This is further

justified by the fact that inspections are far easier, safety is inherently increased (e.g., less height means fewer accidents, easier abort scenarios, huge reduction of power levels, no oxidizer for the first stage, etc.), the design margins are greater and testing/maintenance is less frequent. This is valid only by using unaltered, commercial turbofan aircraft engines and aluminum based airframes. Finally, the first stage is the largest due to gravity losses and structural considerations.

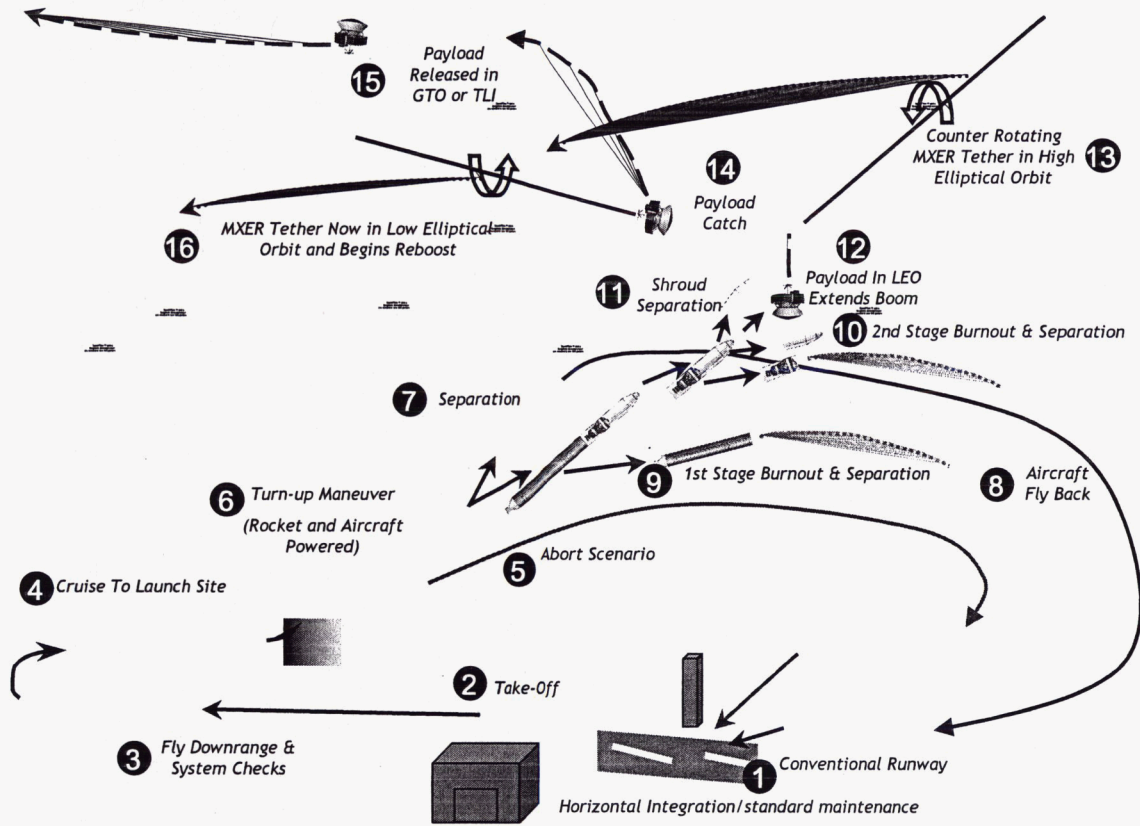


Figure 1: Paradigm Shifting ETO Architecture Launch Sequence

The reduction of first stage mass is dramatic in reducing the amount of expended hardware. It is important to note that the first stage of a conventional rocket is often considered 'efficient' in terms of mass fraction; typically 83% – 94% propellant for solid rocket motors and 67% - 90% for liquid rocket motors.⁹ Yet, this is misleading when compared to the amount of orbital energy it imparts to the payload. The Shuttle, for example, expends roughly one quarter its total propellant mass to obtain "air launched altitude" (~35,000 feet or ~10 kilometers), yet only 0.16% of the required kinetic energy to orbit is acquired!

The standard cost methodology will require a slight modification when evaluating air launch concepts. The approach in this paper is to cost the ETO transit in stages. The aircraft is not expended, which should lead to a reduced launch cost by decreasing the expended fraction, "f". This is the cost model that clearly shows the significant benefits of a reusable single stage to orbit (SSTO). For an air launch system the model should be implemented in stages because the dry mass of an aircraft is very large compared to that of a first stage rocket casing or tankage/engines. This may only be a trivial and intuitive modification, but without it, one could simply reduce launch costs by adding weight to the aircraft. Equation 7 highlights this problem.

$$\lim_{M_{\text{aircraft}} \rightarrow \infty} \frac{M_{\text{Expended}}}{M_{\text{Expended}} + M_{\text{aircraft}}} = 0 \quad f \equiv \frac{\text{Expended Hardware}}{\text{Total Hardware}} = \quad (7)$$

The basis of the analysis starts with the mass summary in Table 2. This data was gathered from various published sources or reasonable engineering estimates. The “payload” is the total rocket mass that is delivered to an undemanding altitude of 10 kilometers (~35,000 feet). This assumes that the vehicle (aircraft or booster rocket) is capable of getting the rocket stage to that altitude with a speed roughly of Mach 0.75 and a high gamma angle (~45 degrees) at separation. It is considered the ‘optimum’ air-launching condition. The Crossbow (Cargo ROcket Space System BOx Wing) design is based on a Delta IV Medium rocket capable of a Delta IV-Heavy payload class to LEO. Its liquid hydrogen/oxygen engines were selected to be three expander cycle engines (250,000 pound class RLX) in the first stage rocket and one in the second stage to increase reliability and decrease cost. The low throttle startup of the first stage engines was assumed adequate thrust augmentation to perform the turn-up maneuver at altitude. The other three aircraft listed in Table 2 are not capable of this operation and have additional issues with a top-mounted rocket separation. The two rocket booster stages lack all the safety, cost and operational efficiencies that horizontal aircraft operations have to offer.

The simple method of correcting the cost model for air launch is to cost each stage separately. As with the booster, there are development and purchase costs associated with an aircraft, but these costs are addressed later. Therefore the new cost equation becomes:

$$C_T = C_T \text{ 1st Stage} + C_T \text{ 2nd Stage} = [c_p M_p + c_L L] + [(c_h f R) + (c_p P) + (c_L L R)] M_{PL} \quad (8)$$

The second architectural innovation is the implementation of a momentum exchange tether at the top of the rocket trajectory. The tether is the only in-space concept, other than chemical or Nuclear Thermal Rocket (NTR) propulsion, that offers high thrust and can operate deep in the Earth’s gravity well. Despite any performance advantage a nuclear thermal system may have over chemical, it will certainly be appreciably more expensive to build and operate. This is because of prudent security and safety regulations that are necessary and extensive, as well as the added costs associated with the fear and general mistrust of such systems by the public. The other key factor is that it is questionable if such a system could ever be safely reused around the Earth after appreciable fission products have been built up within the reactor core. Thus, conventional fission reactors are not viable as a cost-cutting architecture change for ETO. However, the tether transcends across the high thrust of a chemical stage, the practical reusability and safety not found with the NTR in Low Earth Orbit (LEO), and high specific impulse of an electric space tug. These attributes allow the tether to couple well with the ETO transport system and provide large reduction in the launch vehicle size.

Table 2: Summary of First Stage Characteristics

	Expended Hardware (kg)	Total Hardware (kg)	Dry Mass (kg)	Max (min*) Propellant Mass (kg)	Max Payload Mass (kg) To 10 km	GLOW (kg)	Cost (Millions)
Shuttle Solid Rocket Motor	88,000	88,000	88,000 ¹⁰	502,000 ¹⁰	775,000 [†]	1,365,000 ^{††}	~\$100*
Delta IV 1 st Stage	26,701	26,760	26,760 ¹⁰	199,600 ¹⁰	475,000 [†]	701,400 ^{††}	~\$75*
Boeing 777-200 (Commercial)	0	145,149	167,829 ¹¹	145,541 ¹¹ (20,000)	157,218**	345,047 ¹¹	\$140
Boeing 747-400 (Commercial)	0	179,015	179,015 ¹²	164,0640 ¹² (20,000)	163,859**	362,8740 ¹²	\$225
Russian Antonov-225	0	285,000	285,000 ¹³	300,000 ¹³ (65,000)	250,0000 ¹³	600,000 ¹³	\$300 ¹³
Air Launch (Crossbow)	0	230,000***	230,000***	(15,000)	255,000	500,000*	\$300

* Estimated value for air launch case.

** Calculated by subtracting the min propellant mass and dry mass from the GLOW.

*** Calculated by subtracting the max payload mass (230,000 kg 2-stage rocket & 25,000 kg spacecraft payload) and max aircraft propellant mass from the GLOW.

† Determined from the rocket equation, using 1200 m/s delta-v to 10 km altitude.

†† Sum of the payload, dry mass and propellant.

Table 3: Summary of Launch Vehicle Parameters

	f	P	R
Air-Launch (Crossbow)	0**	0.06 (NA)	9.2(NA)
Orbit Injection Stage for Air-Launch	1	11	1.5
Delta IV*	1	32	4.2
Shuttle*	0.2 – 0.3	81	14.3
Chemical TLI Engine	1	5	0.5

* Single system to 300 km circular orbit.

** Assumed negligible

The Momentum eXchange Electrodynamic Reboost (MXER)^{14,15} tether is a long cable-like structure in an elliptical Earth orbit whose synchronous counter-rotation allows a LEO payload to be caught and thrown to a high-energy orbit such as Geosynchronous Transfer Orbit (GTO) or Trans-Lunar Injection (TLI). The top right corner of Figure 1 illustrates the fundamental concept. The orbital energy transferred by the MXER tether to the payload (i.e., the momentum exchange) is restored to the tether via electrodynamic tether propulsion. This technique uses solar power to drive electrical current through the tether, resulting in a magnetic interaction with the terrestrial field. The current must flow from one end of the tether (i.e., from an anode coupled to the space environment) and be emitted at the other end (typically using a hollow cathode, but other methods are possible). Since the Earth itself is the source of momentum, reboost thrust is generated without using propellant.

The MXER tether system used as the baseline is a conservative design, using today's materials and a practical engineering safety factor of 3. It also assumes a minimum 60-day reboost time between uses; far above the nominal 30-days that is a practical limit. It is designed around a 2500 kg payload thrown to TLI and a 10:1 tether to payload ratio. A single launch (i.e., Delta IV Heavy or Sea-Launch) is used to place the entire MXER facility into orbit. The upper stage booster can be held as counter-mass, but was not required in this point design. Flywheel and solar panels were the basis of the power subsystem and aluminum wire carried by a Zylon strength-tether composed the ElectroDynamic (ED) tether. The catch and release mechanism assembly is a new design recently tested and the pure strength-tether is assumed to be a Hoyt tether construction of coated Zylon.¹⁶ The entire system length is on the order of 100 kilometers.

A cost comparison of using MXER versus an all chemical system is shown for the baseline MXER design by adding a third term, or stage, for TLI. Because the maturity of the system is still low, the cost estimates were also varied for sensitivities to the baseline design. Since MXER is fully reusable and propellantless, the primary costs are operations overhead and the fabrication and deployment costs amortized over the number of tosses to TLI within the MXER orbital lifetime (nominally this is limited to ten years due to passing through the radiation belts and micro-meteor/orbital debris). The ostensible approach would be to use a high flight rate for an economical justification; the baseline flight rate is six tosses per year while the economic assessment ranges from 52 to, as low as, one toss per year. Finally, the operations cost of MXER is unknown, but conservatively assumed for this analysis to be two orders-of-magnitude higher than other TLI systems operations cost. The increase in operations costs is due to the necessary additional tracking of the MXER tether during the catch and throw sequence, re-boost phase, and while it is not in use.

RESULTS

With conservative inputs for the air launch costs and congruent rocket data for the different rocket stages we can easily see a cost savings trend of ~10% for the air launch case. In actual implementation, air launch values should have little uncertainty in true cost estimation, while rocket numbers have historically been severely underestimated. What is not seen are the

many intangibles that this air launch architecture provides. This simple costing model does not account for real-world added cost such as flight delays due to weather. The aircraft can be assumed to conduct any mission from a number of airfields and if the primary airfield is safe for takeoff, the aircraft can often fly around many weather systems and perform the launch operation. Safety and abort scenarios are another financial factor often left out of cost models; high insurance premiums when there is no possible recovery of a satellite costing upwards of a billion dollars. Budgetary comparisons of this kind never make the assumption of a loss-of-vehicle accident with the cost implications of recovery, investigation and return-to-flight processes. No one argues that today's planes are not appreciably safer than a rocket booster. Subsonic air launch has the added advantage of many aircraft in operations: a significant factor identifying and correcting anomalies before they lead to catastrophic failure. Readily available parts at commercial prices not only lowers maintenance cost, but also, the cost of downtime for the entire system, schedule slips and launch preparation rework. These and many other unaccounted budgetary forces suggest the real operation cost reduction could be substantially greater than using a conventional booster rocket stage.

Table 4: Cost of Payload to LEO

	Baseline Cost per kg of Payload to LEO (Per lb)
All Chemical ETO	\$16,800 (\$7,650)
Air Launch with L_{ox}/L_{H_2} Orbit Injection	\$14,500 (\$6,600)
Effective Cost to LEO Using MXER*	\$450 (\$200)

* Due to reduced non-payload mass necessary for TLI - cannot be realized for payloads to LEO.

The effect of a MXER tether-styled architecture on ETO is markedly more pronounced. Fundamentally this is an inherent characteristic of the rocket equation itself. The exponential nature of the rocket equation places a premium on every kilogram added at the end of the trajectory. This is easily demonstrated when the payload mass creeps higher than projected. The planned launch vehicle dynamically grows in size/mass, which is directly proportional to cost if it is a "rubber vehicle" design. Otherwise, the next size vehicle must be selected up until no existing launch vehicles can perform the mission. A similar example can be given where actual propellant requirements are used instead of the ideal calculated amount. Tank ullage, feedline volumes, safety margins (i.e, tank metering error tolerance) and other factors incessantly increase the required propellant mass margin. This requires even more fuel to accommodate the weight growth at the top of the trajectory. The extra fuel is exponentially compounded so more fuel is required in an iterative fashion, often ending in a non-converging solution and flustered design engineers!¹⁷

Conversely, any small reduction in ΔV requirements at the end of flight magnifies the drop in total launch vehicle size and cost. Momentum exchange space tethers allow payloads to be transferred to higher orbits without using that last volume of rocket propellant. As seen in Figure 2, a 5 year lifetime tether with only 2 launches a year reduces the cost per kilogram by approximately 50%. That is accounting for the tether station, its initial launch and yearly operational cost. Another conclusion can be drawn is that this particular tether architecture requires a minimum of 5 uses to "breakeven" with the all-chemical lunar mission scenario. Beyond that point the tether saves on the order of 10% to 15% for the 1-year tether lifetime each time it is used. The 5 and 10-year lifetime tethers reduce the cost from 50% to 75% when the yearly launch rate is at least 2 or more over their respective lifetimes. The more the system is used the better the financial benefit and the lower average cost becomes (although asymptotically as it approaches the fixed costs required for each flight).

Several other cost sensitivities trades were conducted with the MXER tether system as defined in this study. In Figure 4, the MXER to Payload Mass Ratio can be as large as 45 to 1 for "breakeven", as long as it is used for 10 years. This is a fantastic mass margin, as the low end has been projected at a mere 6 to 1 (throughout this study, the ratio was set at the practical value of 10 to 1).

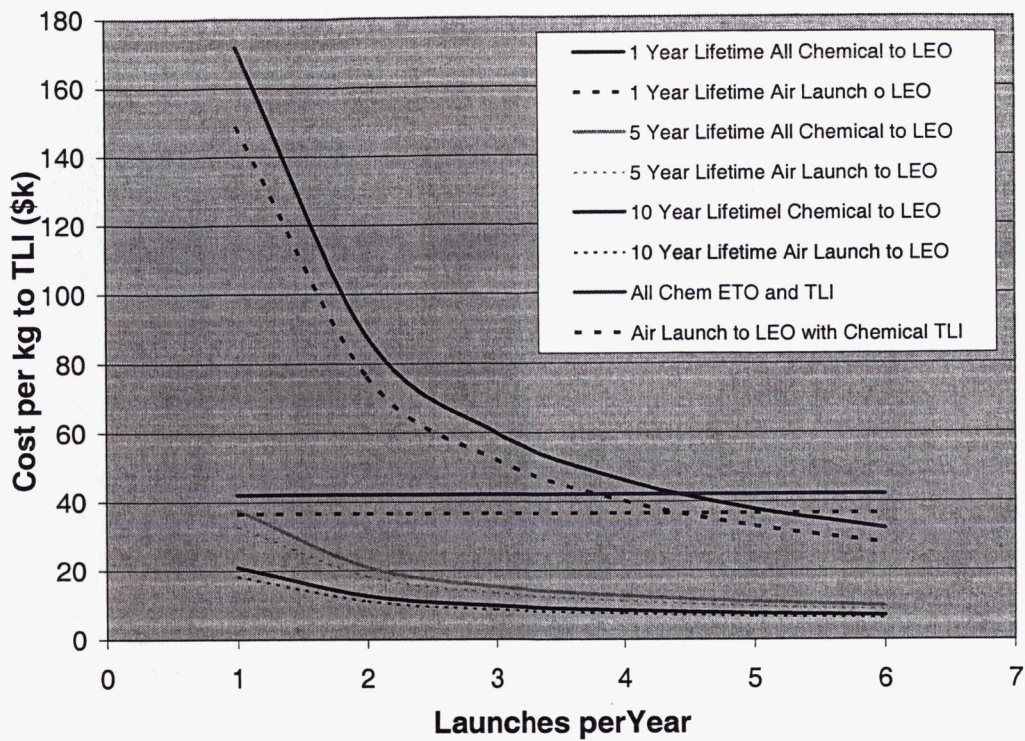


Figure 2: Comparison of cost per kilogram of payload mass to TLI using a chemical injection stage versus MXER.

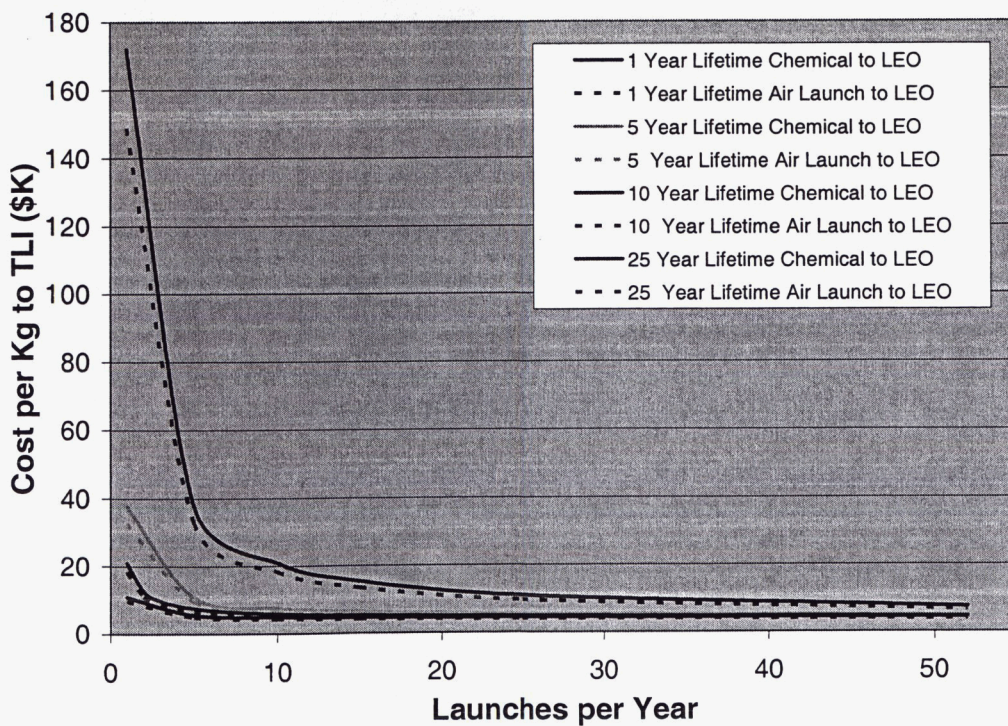


Figure 3: Effect of MXER Lifetime on the cost of payload mass to TLI.

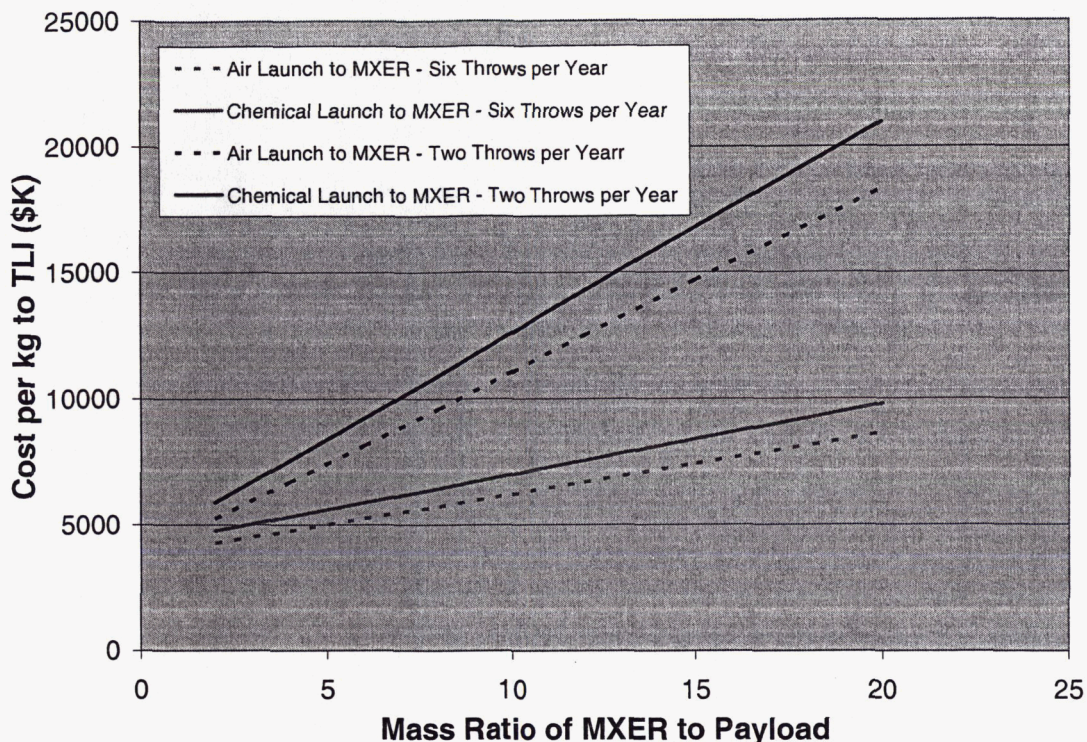


Figure 4: Effect of MXER mass ratio on cost to TLI assuming no on-orbit assembly.

DEVELOPMENT COSTS

The development costs associated with new space technologies are typically very large and always difficult to economically justify. High development cost is the primary driver for governmental led development of new technologies without an immediate and guaranteed, commercial, for-profit application. In the two architectures presented here, there are strong arguments for lessening the inherently high risk found in any space technology program. Air launch particularly has a unique spin on “subsidizing” the development cost. An aircraft that can be designed for a dual purpose such as air-launch and cargo transport could provide a substantial commercial benefit and reduce the governmental development burden. For example, the development of a MXER system or a new aircraft might be on the order of \$1 Billion, and would therefore require a considerable number of launches to “breakeven”. Using the scenario of a 20,000 kg payload to LEO, this might mean 23 launches to LEO (totaling ~450 mT) to achieve breakeven for the aircraft and 14 throws by the tether (total of 35 mT at 2500kg per satellite) to TLI. While this is a strong deterrent of “new” technologies, it is comparable to the total amount of revenue generated by all commercial launches within a single year. Though it is unlikely that more than 20% of commercial launches per year would take advantage from a single air-launch development, this is a reasonable governmental path toward a low-cost, reliable, commercial launch capability. The other rationale to justify the initial development cost is the potential for air cargo transportation and a heavy military–lift capability, both presently in distressing shape within the United States. Even the aging B-52 fleet, as well as special aircraft applications such as laser-borne systems, can be cost-effectively replaced with the pod-hauler design. In the tether’s case, less direct commercial benefits are seen (beyond spin-off technologies such as more durable cables). However, the payback potential is tremendous for a sustainable lunar infrastructure¹⁸ and that is enough justification for the Government to pursue it.

NON-COST BENEFITS AND COSTLY APPROACHES

Many of the unaccounted economic benefits were mentioned in the analysis for both air launch and momentum tether thus far. Much of the information and specifics given require

dedicated papers detailing each of the architectures to fully cover their scope and justification. However, a short summary of some other considerations is necessary to be complete in this text. Flexibly in trajectory selection, independent of launch site, and bad weather avoidance do lead to financial benefits. Being able to fly downrange of the launch site and then land the aircraft at its departure base of operations eliminates the need of many multiple landing and abort sites. Since a reusable first-stage rocket is the next logical step envisioned for air launch, it would also be highly advantageous for the departure airfield to serve as its glide-back runway without requiring the stage to complete an orbit or even make a turning maneuver. Even the often cited “negative” to air launch (i.e., limited aircraft size prevents rocket growth) is actually an economic benefit in the long run. An inherent assumption in the proposed Crossbow design is the large Delta-IV Heavy payload class, going beyond this would exceed conventional runway and landing gear capabilities and rapidly drive costs up. Development and operations costs *skyrocket* with vehicle size, yet aerospace decision makers often default to growing the rocket size to fix every issue. This disregards the rare exception of a very large space asset that might require extensive on-orbit assembly, with its associated cost (note, no launch vehicle is capable of all missions particularly that of a giant Saturn-V class expendable). The attractive attributes of limited rocket size (i.e., Delta IV Heavy or Atlas V class payload using a Delta-IV) include:

- Vehicle price to be within reach of ‘other’ customers
- Normal size manufacturing, shipping & inspection
- Lower development costs & risk (i.e., mass determines cost, schedule, test difficulty, etc.)
- Less infrastructure (i.e., cryogenic fuel storage, building space, cranes, etc.)

Limited payload size attractive attributes include:

- Automatically generates higher flight rate
- Keeps insurance low for individual payloads
- Single payload flexibility and convenience

The Crossbow system was primarily derived from a cost and safety requirement standpoint and not the typical performance metrics classically used as the starting point for an engineering design. Of the many benefits mentioned, most stem from the idea that the proven and unaltered commercial aircraft/runway system is well quantified and highly optimized. It is understood there is a lower limit to the size of the LOX/LH2 rocket such that it must be carried and the Crossbow is inherently a large aircraft. Therefore, simple scaling up of subsonic airliner technology is required, but is not inhibited by any aeronautics constraints and will still yield low cost and high reliability. Modifications such as rocket assist, new engines, supersonic flight, and runway modifications, are considered to violate the two main objectives for the aircraft stage. Top or wing mounting of the “second stage” rocket; use of any explosives or solid rocket motors; other separation operations; use of other rocket engine cycles (i.e., high pressure engines like the SSME); only a single rocket stage; wings on the rocket; are all approaches that inherently escalate cost on the rocket side. Thus, embracing an unfavorable cost-to-benefit ratio with a higher than optimum technology or methodology is a common flaw.¹⁹

The tether design is not as overwhelming as the air launch approach just discussed, but it has a few similar design-space “edges” that are prudent to avoid. Leaving the detail and specific justification to future papers, the most prominent are: designing with materials not presently available; not including a structural safety factor; using chemical rockets (or nothing) for reboost; extraordinarily long tethers (i.e., 1000s km); dipping far into the Earth’s atmosphere for the catch²⁰; single strand tether construction. And of course, when both a tether and air launch architecture are employed together the following should be avoided: mismatch on payload sizes; deletion of the rocket “second stage”; exclusive use of the aircraft for the tether operation (due to the long reboost times); launch vehicle recovery and flight preparations longer than the tether’s next available capture opportunity.

The last non-cost benefit that must be mentioned is the architecture perception or human appeal. This is often a most underrated and misunderstood factor in major civil space projects, yet it is often the undoing of many approaches. There must be sound “buy-in” by a majority of the stakeholders who put up the capital for the development, implementation and operations (whether public or private). In the few private ventures that have emerged, this is one of the highest factors

– often at the expense of sound engineering reason. The ‘allure’ of the space elevator is so great that funding is being put up without even considering its practicality or financial “breakeven” point. In the governmental sector, the pendulum has swung to the opposite end, a mindset that lacks any excitement, innovation or creativity that will ignite enthusiasm with many. The general aerospace community has become excessively risk adverse and now totally relies on existing flight hardware no matter how outmoded (e.g., 486 equivalent CPUs) or cost ineffective (e.g., recovery and refurbishment of the solid rocket motor boosters). Technology development and infusion of either new architectural or subsystem alternatives are rarely embraced.

There has to be inherent long-term buy-in on any ‘sustainable’ space architecture. One way is to be glitzy with the architecture such as a single-stage-to-orbit, air-breathing, Mach 25, super plane (i.e., the so called Orient Express). That sold and *sold for a high price*, but the required breakthroughs never materialized and the enthusiasm quickly ceased after no progress was seen. The other tactic is to offer innovation that transcends what is today, into a new paradigm. That slow, but steady commitment to improve life on earth can be supported by all political perspectives as well as the average person over the long time scales it takes to complete an ambitious project as lunar colonization. The essence of the air launch/Crossbow blueprint is the pod-hauler design and the idea that NASA, in its effort to permanently conquer the Moon, will completely transcend the current airline industry and support the security of the Nation.. MXER tethers seen twirling in the sky without needing even a pair of binoculars would inspire the young to study and become more enterprising and adventurous. Tether technology has growth potential over the long horizon, leading to bigger momentum systems, lunar slings, space station reboost, lunar elevators, and more.²¹ Hopefully, such long and short term benefits may excite the imagination long enough to make it a reality.

CONCLUSIONS

There are a number of economic themes that are suggested for obtaining affordable and sustainable ETO launch costs. Two transportation architecture changes are presented at either end of a conventional two-stage rocket flight. The first is air launch assist circumscribed in unique corner of the air launch trade-space (i.e., a large pod hauler like Crossbow). The other end of the rocket flight is assisted by a momentum exchange tether (i.e., an in-space asset like MXER). Air launch has an analytically justified cost reduction of ~10%, but its intangible benefits suggest real-world operations cost reductions much higher. It has inherent launch safety, mission risk reduction, schedule enhancements, favorable payload/rocket limitations and other practical functions. Leveraging an aircraft that would not solely be used for air-launch (military transport, commercial cargo, public outreach activities, etc.) could economically justify air-launch.

For payloads delivered beyond LEO, the most effective method of reducing ETO costs may not be in the ETO vehicle, but rather by increasing the ratio of useful payload to mass delivered into LEO. Momentum exchange tethers are shown to have upwards of a 50% cost reduction for ETO and are the only other technology, besides chemical rockets, that is practical to operate deep in the Earth’s gravity well. Both systems work to enhance conventional rocket technology without reaching for exotic or risky materials or methods. Non-cost benefits abound for both the aircraft and tether architectures and their combined effect gains even more benefits. MXER is truly a solution for a sustainable lunar architecture, but is only practical if it will be used on a consistent basis. Changing the existing ETO rocket paradigm takes these two architectural alterations to make space flight sustainable and affordable.

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